Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Fakulteten för naturresurser
och lantbruksvetenskap

Kristin Boye, Nicholas Jarvis, Julien Moeys, Mikaela Gönczi and Jenny Kreuger

Pesticide Run-off to Swedish Surface Waters and Appropriate Mitigation Strategies

– a review of the knowledge focusing on vegetated buffer strips

Photos: Nicholas Jarvis, Kristin Boye

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KompetensCentrum for Kemiska Bekämpningsmedel
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Centre for Chemical Pesticides
Swedish University of Agricultural Sciences

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Contents

Summary

Environmental monitoring has revealed that pesticides regularly enter surface waters in Sweden. Mitigation measures to control point sources and spray drift have successfully reduced pesticide concentrations in natural waters, but concentrations still sometimes exceed ecotoxicological guideline values. In addition, the EU directives on water (2000/60/EC) and sustainable use of pesticides (2009/128/EC), and the regulations regarding placing plant protection products on the market (EC 1107/2009) stipulate that mitigation strategies should be developed against diffuse sources, such as surface run-off and drainage. This report presents a compilation of existing knowledge as data support for the relevant authorities in the implementation of run-off mitigation strategies in regulatory and subsidy systems.

The report describes a number of measures (vegetated buffer strips in particular, but also wetlands, ditch management, integrated pest management and other management strategies) to reduce the risk of surface run-off of pesticides. The report also evaluates the validity under Swedish conditions of the R1 scenario in the PRZM-in-FOCUS model for assessing the risk of pesticide concentrations exceeding the ecotoxicological guideline values due to pesticide transport through run-off.

In Sweden, the majority of surface run-off occurs during snowmelt, when pesticide losses are unlikely. The temporal and spatial incidence of run-off events during the growing season and the amount of pesticides transported in this way are currently unknown. Phosphorus models estimate that up to 33% of total annual water flow enters water courses as surface run-off in the worst case scenario, and around 10% on average, but lack of model calibration data renders these estimates highly uncertain. Field data from a drained silt loam (considered to represent the 95^{th} percentile worst case for run-off under Swedish conditions) suggest that 35-50% of total monthly water flow during summer (May-September) occurs as surface run-off. Thus, surface run-off may contribute considerably to pesticide transport locally, but is still considered unlikely to be of major importance on a national level, although data are lacking to confirm this assumption. Therefore, local adaptation of mitigation measures is deemed a more efficient strategy for Sweden than general solutions, such as mandatory vegetated buffer strips along all water courses. This would also simplify coupling to other environmental mitigation measures, e.g. concerning nutrients and biodiversity, and increase acceptance among farmers. The R1 scenario in PRZM-in-FOCUS greatly overestimates the risks of run-off and erosion for Sweden, since the assumptions on soil and weather conditions are more extreme than is realistic for Sweden. Thus, alternative solutions suggested in this report for assessing pesticide run-off risks in Sweden are: 1) developing a Swedish scenario for the PRZM model; 2) expanding the Swedish groundwater scenario for the MACRO-in-FOCUS model to include run-off estimation; and 3) establishing a system for local run-off mitigation that is sufficiently reliable to justify the assumption that pesticides will rarely enter surface waters through run-off. It is strongly suggested that research and monitoring projects be supported to provide a better database on which to build risk assessment scenarios and risk management strategies.

Swedish summary

Ytavrinning är en av flera möjliga diffusa spridningsvägar för växtskyddsmedel till ytvatten. Motåtgärder mot ytavrinning av växtskyddsmedel, med speciellt fokus på skyddszoner, har aktualiserats genom EU:s antagande av ett nytt ramdirektiv (2009/128/EG)[1] för hållbar användning av bekämpningsmedel och genom riskbedömningsrutiner vid produktregistrering av växtskyddsmedel enligt växtskyddsmedelsförordningen (EG 1107/2009)[2]. Med anledning av detta har problemets omfattning i Sverige och olika motåtgärders relevans och effektivitet under svenska mark- och väderförhållanden undersökts genom en litteraturgenomgång och intervjuer med svenska och internationella aktörer och experter. Rimligheten i riskbedömningsmodelleringar med R1 scenariot i PRZM-in-FOCUS har också utvärderats för svenska förhållanden.

Bedömningen är att ytavrinning lokalt kan vara av stor betydelse för transport av växtskyddsmedel till ytvatten i Sverige, men att fenomenet troligtvis är begränsat i tid och rum till tillfällen (t ex extrem nederbörd) och/eller platser (t ex erosionsbenägna jordar, traktorspår, området runt dräneringsbrunnar) där särskild risk för ytavrinning föreligger. R1-scenariots mark- och väderförhållanden är inte representativa för svensk åkermark och modelleringarna överskattar troligtvis risken för transport genom ytavrinning. Skyddszoner och andra motåtgärder bedöms effektivt kunna reducera mängden växtskyddsmedel i ytavrinning om placeringen i landskapet och utformningen är rätt. De lokala förutsättningarna i form av t ex topografi (på landskaps- och fältnivå), markegenskaper, brukningsmetoder och grödor är avgörande för vilken typ av åtgärd(er) som lämpar sig bäst och var den/de ska placeras. Att införa obligatoriska skyddszoner längs med alla vattendrag bedöms därför inte motiverat, då den förväntade effekten är låg i förhållande till de stora arealer jordbruksmark som skulle behöva tas ur produktion. Istället förespråkas lokalt anpassade åtgärder, som kan föreskrivas eller ingå i rådgivning och miljöstödssystem. Eventuellt bör ett alternativ till dagens riskbedömningsmodelleringar övervägas för att nå en rimligare försiktighetsnivå i bedömningarna.

1. Introduction

Agricultural pesticides are regularly detected in surface waters in Sweden, sometimes in concentrations that exceed the guideline values established to protect aquatic organisms (these guideline values vary depending on substance) and/or drinking water safety (0.1 µg/L)[3, 4]. In order to achieve the Swedish environmental quality objectives of a non-toxic environment and living lakes and streams, mitigation strategies are therefore necessary. In addition, the EU Framework Directives on water (2000/60/EG)[5] and on sustainable use of pesticides (2009/128/EG)[1] require mitigation strategies to prevent pollution of water. Mitigation measures to control pesticide losses from point sources, in particular spillages during sprayer filling and washing, have already given good results[6]. The next step is to control non-point sources, particularly spray drift, surface run-off and drainage losses. This report deals specifically with surface run-off of pesticides. It was produced at the Centre for Chemical Pesticides (CKB) at the Swedish University of Agricultural Sciences (SLU), at the behest of the Swedish Board of Agriculture (SJV).

The aim of the report was to compile the results of scientific studies and international experiences regarding surface run-off of pesticides and various mitigation strategies, particularly vegetated buffer strips, and assess their relevance under Swedish conditions. The underlying data were taken from international scientific journals, Swedish and international reports from official bodies, interviews with international experts and Swedish researchers, data from environmental monitoring of pesticides and nutrients and discussions with relevant officials in Sweden. The report is intended to provide data support in the implementation of run-off mitigation strategies in Swedish regulatory and subsidy systems, advisory work and risk assessment procedures.

2. Background

In 2009, the European Parliament and the Council introduced a new directive (2009/128/EG)[1] on the establishment of a framework for Community action to achieve sustainable use of pesticides, but a future extension of this to biocidal products is also predicted. The Directive was expected to be introduced into member state legislation by 14 December 2011 at the latest, but in many countries, including Sweden, introduction has been delayed. The Swedish Environmental Protection Agency (SEPA) in consultation with the Swedish Board of Agriculture and the Swedish Chemicals Agency (KemI) drew up a proposal on Swedish implementation of the Directive, which was submitted to the Swedish Ministry of the Environment in November 2009, but progress has since been significantly delayed. The Swedish Board of Agriculture has developed a proposal for a national action plan (Action Plan for Pesticides in Sweden), which is currently out on a round of consultation.

The EU Framework Directive includes regulations on training, marketing, information, application, risk indicators and reporting. Chapter 4, Article 11 presents regulations on specific measures that *must* be taken in order to protect aquatic environments and drinking water. Paragraph 2c in Article 11 states the need for:

> *Use of mitigation measures which minimise the risk of off-site pollution caused by spray drift, drain-flow and run-off. These shall include the establishment of appropriately-sized buffer zones for the protection of non-target aquatic organisms and safeguard zones for surface and groundwater used for the abstraction of drinking water, where pesticides must not be used or stored.*

This means that mitigation measures against surface run-off of pesticides must be introduced into Swedish legislation, but there is scope for freedom of interpretation on how the specified buffer zones should be designed. The concept ‘safeguard zone’ is commonly used to refer to a spray-free and/or fertiliser-free zone which is otherwise treated in the same way as the rest of the field, while the concept ‘buffer zone’ or ‘buffer strip’ is used for a zone that is removed from agricultural production to establish a permanent crop, e.g. grass, bushes and/or trees.

Surface run-off of pesticides also forms part of the risk assessment that is carried out in conjunction with product registration of pesticides according to the EU Pesticides Directive (EG 1107/2009)[2]. In Sweden, this is done by KemI using as an aid the PRZM model, with scenarios developed by the FOCUS group within the EU for assessing the risk of an active compound from a pesticide being spread to surface waters and groundwater[7]. The scenarios for drain-flows (D scenarios) and run-off (R scenarios) are based on weather and soil conditions in different regions within the EU. For its drain-flow simulations, KemI uses scenario D1, which is based on data from Lanna in Västergötland, and scenario D4, from Skousbo in Denmark. However, the surface run-off scenario (R1) used by KemI is based on data from Weiherbach in southern Germany. KemI has therefore requested an evaluation of the representativity of this scenario for Swedish conditions. The FOCUS group has made the assessment that parts of southern Sweden are covered by the scenario (*Figure 1).* This is based on the fact that the soil type in Weiherbach also occurs in southern Sweden according to the Soil Geographical Database of Europe (scale 1:1000 000) and that climate data and at least one crop coincide with data from Weiherbach[8]. However, this assessment is very uncertain, since soil characteristics can vary locally (on a considerably smaller scale than that in the Database) and since every classified soil type contains a large variation of soil properties in itself. The scenario R1 soils share the properties that they are silts (sand content <15%, clay content ≤35%), free-draining, can be irrigated and are not water-saturated above 40 cm depth for more than 1 month per year, or above 80 cm deep for more than 3 months per year[8].

In addition to risk assessment with Scenario R1, since December 2010 KemI has exercised the option, in accordance with FOCUS recommendations[9], to introduce vegetated buffer strips as a countermeasure in the model (SWAN in FOCUS) for products where the R1 simulation indicates a risk that surface run-off can lead to concentrations above the guideline values in surface water. This has resulted in a small number of products, which would otherwise have been banned, being approved on condition that a permanently vegetated buffer strip (10 m

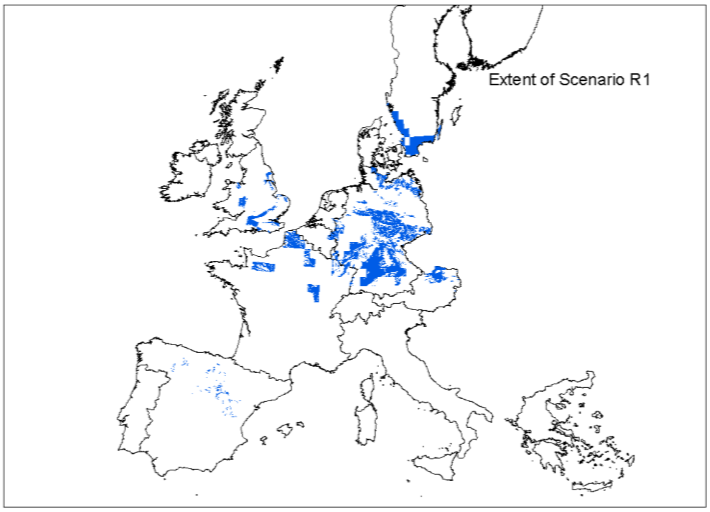

Figure 1. The FOCUS group's assessment of the extent of scenario R1 in the PRZM-in-FOCUS model[7].

wide) is established along stream boundaries in the year before the pesticide is applied. However, this creates a conflict between buffer zones that are eligible for environmental subsidies and vegetated buffer strips stipulated by the pesticide usage conditions. This also probably means arable land being taken out of production on soils where problems with surface run-off are non-existent, without the risks being decreased. In addition, the effects of permanently vegetated buffer strips, and thus whether their use is sufficient to justify pesticide approval on this condition, have not been confirmed under Swedish conditions.

While it is important that risk assessments in conjunction with product registration and any mitigation measures agreed upon are safe and suitable for Swedish conditions, the registration process must be harmonised within the EU. Therefore the EU countries have been divided into three harmonisation zones, with Sweden belonging to the northern zone together with Denmark, Finland, Estonia, Latvia and Lithuania. Products are then evaluated in only one country within a zone, with countries having the opportunity to submit opinions, after which every individual country decides whether the product should be approved. The actual risk assessment is thus only carried out once. It facilitates the risk assessment process if the interpretation and tools are as similar as possible within the zone.

As a result of the great uncertainty that prevails on how the risk of surface run-off of pesticides should be handled in risk management and risk assessment in legislation, advisory services and product registration, the Swedish Pesticide Council (Växtskyddsrådet) requested more supporting data and the Swedish Board of Agriculture granted funding to CKB to make a compilation of existing knowledge in Sweden and internationally, work which resulted in this report.

3. Surface run-off – mechanisms and flow pathways

Surface run-off is water that runs off the soil surface and can arise as a result of the soil being water-saturated (or frozen) or of rainfall/irrigation being so intensive that the water does not have time to make its way (infiltrate) into the soil. Surface run-off as a result of insufficient infiltration capacity can be due to poor soil structure deriving from soil textural properties (e.g. silty soil) or soil compaction (e.g. in tractor tracks) (*Figure 2*). In Sweden, surface run-off as a result of water saturation is more common, since the majority of surface run-off occurs during snowmelt, when frost renders the soil impermeable and large amounts of water collect within a short period (*Figure 3*).

Surface run-off begins as diffuse flows known as sheet flow, but rapidly transitions to concentrated flows in rills (*Figure 4*). These are often particularly apparent in wheel tracks or in small depressions in the landscape. In the worst cases, these rills can coalesce, forming ravines. These are often associated with surface run-off on strongly sloping land, but water flows on the soil surface and pollutant transport can occur even on gentle slopes[10, 11]. However, erosion (i.e. particle transport) is more widely linked to soil slope, since increased slope leads to increased flow velocity. The erosion force and flow velocity also increase with increasing concentration of flow. It is important to point out that the local topography within the field is critical for how the water flows[10, 12], whether rills and ravines are formed and whether water leaves the field as surface run-off or has time to infiltrate in local depressions or areas with higher infiltration capacity.

Figure 2. Surface run-off after heavy rain on a light clay (far left) and as a result of decreased infiltration capacity owing to soil compaction and damage to macropore structure in wheel tracks (centre and right). Photo: Nicholas Jarvis (left and right), Örjan Folkesson (centre).

Figure 3. Surface run-off and erosion after snowmelt on Swedish arable land. Photo: Eskil Nilsson (lower left) and Örjan Folkesson (other pictures).

Even if surface run-off does occur, this does not necessarily mean that it contributes to transport of pesticides to surface waters (or other undesired recipients), since this also requires the pesticides to be mobilised by the water and the flow to reach the recipient. The risk of a pesticide accompanying surface run-off flow is dependent on the binding and degradation properties of the compound[13-15] and soil properties[10]. In general, the risk is higher the earlier the surface run-off occurs after pesticide application[16-18], the stronger the erosive force, whether the soil structure is damaged[19] and the higher the concentration of pesticides on the soil surface. Herbicides are therefore especially prone to be carried off in surface run-off, since they are spread before crop emergence during periods when the risk of surface run-off is higher[9]. The same applies to soil disinfectants. The probability of the flow reaching the recipient is higher for concentrated flows, in areas where the topography and/or soil texture are unfavourable, if the soil structure is destroyed and/or water-saturated in the vicinity of the recipient, and if there are shortcuts in the form of e.g. ditches, wheel tracks, footpaths or roads.

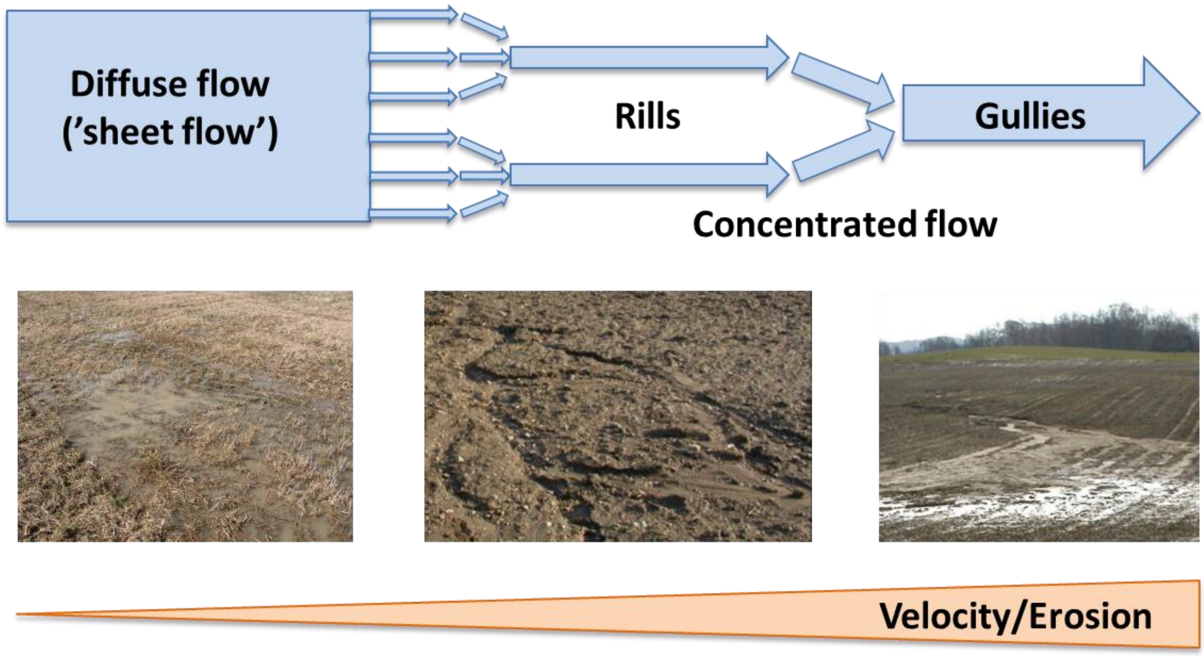

Figure 4. Schematic diagram and photos showing different types of surface run-off flows. Photo: Nicholas Jarvis (left), Kristin Boye (centre), Örjan Folkesson (right).

Another type of shortcut consists of structures that cause water to infiltrate rapidly, but where the transport occurs instead via tile drainage pipes, groundwater or rapid soil flows. Examples of such shortcuts are drainage wells, cracks and vole tunnels. On the other hand, there may be physical barriers in the form of small grass strips or similar that are created during soil tillage and which stop the flow before it leaves the field. The topography within the field can also be such that surface run-off is formed on part of the field and then infiltrated in another part, if the field levels out or if there are local depressions. It is therefore important to know the flow pathways the water follows from pollution source to recipient if effective mitigation measures are to be implemented[20, 21]. It is often only a minor part of the soil that generates surface run-off flows and not all of the flows generated reach water courses[22]. The concept of connectivity is used to describe for example how flows or landscape elements act together. Connectivity, i.e. interconnected, fast transport pathways, is required if pollutants are to reach surface waters (*Figure 5*). Therefore mitigation measures should be directed to interrupting this, so that the flow is slowed down and degradation and binding process have time to act. Connectivity is difficult to measure, but research and model development work currently underway can be used to carry out risk assessments based on connectivity in the landscape[22, 23].

Figure 5. Examples of how connectivity affects surface run-off flows. Left: Shortcut created where a horse path crosses a ditch, leading past a vegetated buffer strip straight down into a river (Photo: Kristin Boye). Centre: Soil erosion by surface run-off flows around a drainage well (Photo: Örjan Folkesson). Right: Surface run-off flow that has entered a field but has then stopped and is infiltrating into the soil (Photo: Kristin Boye).

4. Mitigation measures against surface run-off of pesticides

Surface run-off of pesticides is considerably more complex than spray drift, since there are so many different factors that affect where, when and how transport occurs. Soil properties, topography, vegetation, hydrological conditions and substance properties interact. Therefore local conditions are decisive for the routes, locations and timing of surface run-off and whether pesticides are transported in surface run-off. In order to achieve maximum effect from various mitigation measures against surface run-off, it is therefore essential to take local conditions into account[14,18,20,21]. Furthermore, according to the experts, the various mitigation measures should be regarded as a collection of tools to be employed in different combinations depending on the local conditions, not as separate solutions[21, 24-26]. The European Crop Protection Association (ECPA) has initiated a project entitled Train Operators to Promote best Practices and Sustainability (TOPPS)[27], with the aim of developing, demonstrating, training and promoting Best Management Practices (BMPs) for sustainable use of pesticides in order to protect natural water resources. The first part of the TOPPS project, TOPPS-Life, is focusing on point sources, which often arise from spillages during filling and washing of sprayer equipment. The second part of the TOPPS project, TOPPS-Prowadis, is still in progress and therefore to date there is only a preliminary report, which was presented at a workshop in Brussels in April 2012[24]. TOPPS-Prowadis is focusing on the diffuse sources spray drift and surface run-off. For spray drift, an internet-based tool is being developed that will essentially resemble the Swedish aid[28]. For surface run-off, a decision tree will be developed as an aid in the process of selecting mitigation measure/s. The starting point is a three-step concept in which the intention is that advisors and farmers will work together within a catchment area to counteract the problem of surface run-off transport of pesticides:

1. Diagnosis – collection of available data from local farmers, together with observations in the field and GIS simulations in order to identify flow pathways in the catchment area in question.
2. Toolbox – an inventory of various mitigation measures: method, function, implementation, upkeep, effectiveness in different conditions, additional environmental benefits that can be gained, disadvantages and complications, the availability of subsidies and compensation or other income, cost calculations.
3. Best Management Practices (BMPs) – the measures that are most appropriate in the area in question are chosen with the help of the diagnostic results and on the basis of the economic conditions.

This concept is based on the methodology (CORPEN)[29, 30] that is used in France and provides locally adjusted solutions that have a good likelihood of being accepted and implemented by farmers[24]. The good effect of combining different methods in order to decrease surface run-off of pesticides has been demonstrated in an American study, in which the toxicological effects on fish and shrimp populations decreased by 90% in catchment areas where risk management measures in the form of integrated pest management, sedimentation ponds and other BMPs has been directed towards surface run-off of pesticides[31]. Good results have also been obtained in England by using targeted, locally adapted mitigation measures to control diffuse pollution sources from agriculture[32].

The aim of the present report was to investigate the effectiveness and appropriateness of different mitigation measures under Swedish conditions. The focus was on vegetated buffer strips in particular, but other mitigation measures intended to stop any surface run-off flow that arises are presented as thoroughly as possible on the basis of available research results. Mitigation measures that aim to decrease the risk of surface run-off occurring at all, or of pesticides accompanying any surface run-off arising, are presented briefly. Of course, many mitigation measures have a number of other positive effects and therefore the choice of measure/s depends on the environmental benefits prioritised based on the specific situation.

4.1 Vegetated buffer strips

Vegetated buffer strips are permanently vegetated areas of agricultural land that are intended to slow surface run-off flows and decrease the transport of water, sediment and pollutants (nutrients, pesticides, etc.). In principle, there are five different kinds of mechanisms operating in the vegetated buffer strip (*Figure 6*): sedimentation, infiltration, adsorption, degradation and dilution. Plant uptake can also make a contribution[33]. Infiltration is often the most important mechanism for achieving a total reduction in water and pollutant loads being transported through surface run-off[34]. Sedimentation is important for particle-bound substances, while the other mechanisms can contribute to varying degrees to decreasing the concentrations of substances in the water phase. For pesticides, slowing water flows is an important function in itself, since the longer the contact time with the soil, the greater the opportunities for degradation and adsorption (i.e. binding to soil particles). In addition, vegetated buffer strips often have a higher organic matter content than the fields above[35], which further increases the adsorption capacity. This applies especially to particulate organic material (plant residues)[36]. The degradation rate can also be greater if microbial activity is stimulated by the conditions in the vegetated buffer strip[33].

Vegetated buffer strips can be positioned within fields where the risk of surface run-off is particularly great (in-field vegetated buffer strips), along the edges of fields (edge-of-field vegetated buffer strips) or along water courses in order to prevent surface run-off flows reaching water (riparian vegetated buffer strips) (*Figure 7*). Grass is the most common plant species, but the vegetation can in principle consist of any plants, as long as they can withstand the flow (e.g. sturdy grasses, bushes, trees). The vegetation should be selected carefully in order to optimise the effectiveness on the actual field based on the objective to be achieved. The primary objective of a vegetated buffer strip is to stop surface run-off and erosion, and to decrease the losses of sediment, nutrients and pesticides. Secondary objectives can be for example to increase biological diversity or create green corridors so that it is easier for animals to move between different biotope fragments in the landscape. In certain cases it may be possible to use the vegetated buffer strip for the production of bioenergy or as a forage ley, in order to decrease the economic losses from taking agricultural land out of production. However, using the vegetated buffer strip as grazing is not recommended, since grazing animals cause soil compaction[37] and increase the risk of nutrient leaching. It is also important that a vegetated buffer strip is not trafficked by agricultural machines that increase the soil compaction[37].

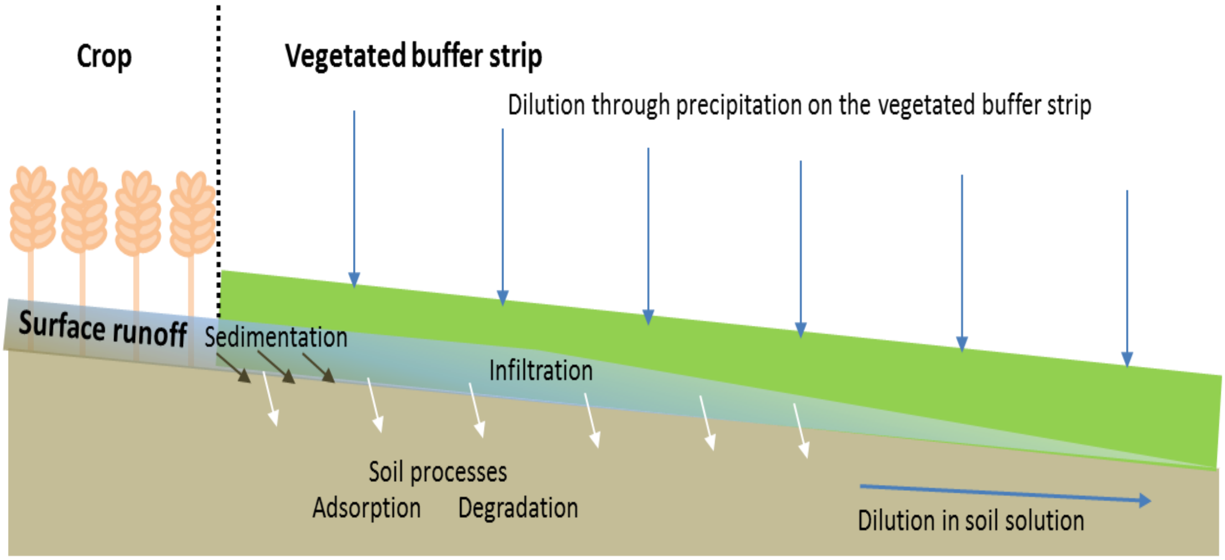

Figure 6. Schematic diagram of the mechanisms that operate in a vegetated buffer strip.

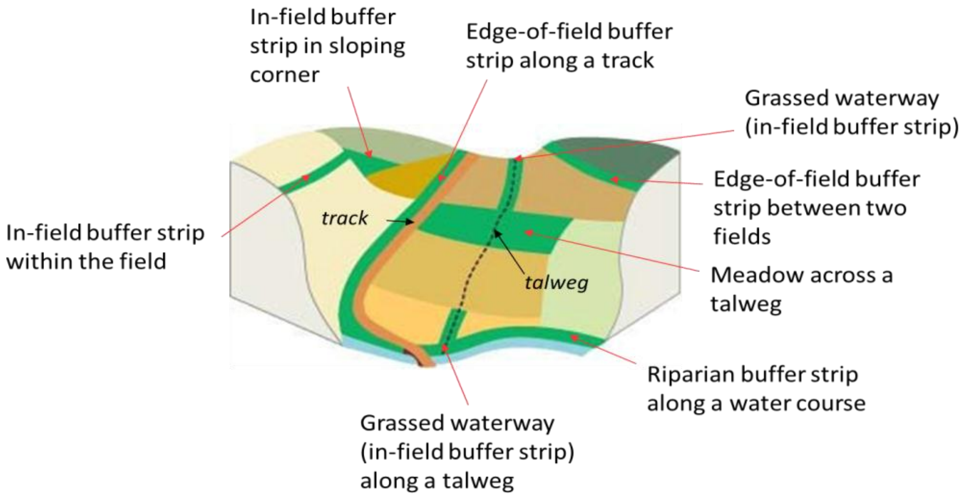

Figure 7. Examples of how different types of vegetated buffer strip can be placed in the landscape in order to effectively stop surface run-off flows[38].

There have been a number of international scientific reviews on the effectiveness of vegetated buffer strips[9, 39-43] and the overall consensus from these is that vegetated buffer strips reduce the amounts of sediment, water and pollutants that are transported through surface run-off, but the magnitude of the effect depends on the local conditions in time and space, the design of the vegetated buffer strip, the type of pollutants studied, and the inflow rate, amount and concentration. It is important that the vegetated buffer strip is positioned correctly in the landscape so that it stops the flow as near to the source as possible, since there is otherwise a risk of water flowing past the vegetated buffer strip in concentrated flows and thus of the vegetated buffer strip losing its effect (*Figure 8*)[21, 44, 45]. If there is a risk of concentrated flow, the vegetated buffer strip can be complemented with a barrier that slows the flow and spreads the water over a larger area[45]. It is also important that the vegetated buffer strip is managed so that it does not lose its effect[41, 46]. Such management involves avoiding and reversing soil compaction and ensuring that vegetation is dense and sufficiently high, that no shortcuts bypassing the vegetated buffer strip arise in the form of concentrated flows or drainage channels, and that the infiltration capacity is not impaired by sedimented material[37].

The USA and France have devised specific recommendations on the design and placement of vegetated buffer strips[30, 37] and some research has been carried out on how vegetated buffer strips should be designed to optimise their effectiveness. These research studies have mainly compared vegetated buffer strips of different widths and/or vegetation types, and the results give no clear conclusions. A wider vegetated buffer strip often gives a higher overall effect, but the relationship is not linear[41] and the efficiency per unit area is greater for a narrower (5 m) vegetated buffer strip than a wider (10 m)[47], since the greatest reduction takes place within the first metre or few metres[11, 48]. In addition, the relationship between width and effectiveness applies primarily to particle-bound compounds and sediment, while the effect on water-soluble compounds and small particles (fine silt-clay fraction) is not affected to the same extent by strip width[41]. The slope of the vegetated buffer strip is also important for the width; a steeper slope requires a wider strip to achieve the same effect.

Figure 8. Breakthrough of strongly concentrated flow into a vegetated buffer strip during snowmelt. Photo: Örjan Folkesson.

The choice of plant/s can be important for vegetated buffer strip effectiveness and function[33, 47, 48], although some studies have been unable to find any differences between different types of vegetation[49]. Some species are more sensitive to the toxic effects of pesticides than others and some increase the rate of pesticide degradation more than others, although it is uncertain how species-specific this effect is[33]. Grass is often more tolerant and a coarse, dense grass stand provides good resistance to erosive flows. Bushes and trees have deeper roots, which can increase the infiltration capacity[50], and they add more organic material, which increases the adsorption capacity. The type of organic material also affects the adsorption properties; tree detritus is more hydrophobic than other organic materials on grassland, which results in a higher adsorption capacity for hydrophobic compounds (high K_{oc}), but lower for water-soluble compounds[36]. An additional aspect is that roots can damage, penetrate and clog tile drainage pipes, especially older types, if trees or bushes are planted on drained land. However, drainage pipes in good condition are normally not damaged by roots[51]. Owing to the many influencing factors, a local evaluation of the various advantages and disadvantages must be carried out to determine what is most suitable for the specific situation.

4.1.1. In-field vegetated buffer strips

Design and purpose

In-field vegetated buffer strips are established within the field to slow down surface run-off as close to the source as possible and thereby decrease the risk of concentrated flows and erosion arising. The design of these vegetated buffer strips depends on the local conditions. They can consist of narrow grass-covered strips or hedges along the contour lines on steep slopes, or vegetated zones around drainage wells or in sloping corners of fields. They can also consist of vegetated areas in depressions, where concentrated flow can easily arise.

Effect

Since in-field vegetated buffer strips have very different designs depending on local conditions, it is difficult to make a general assessment of their effectiveness, but with correct placement the effectiveness should be high, provided that infiltration, adsorption and degradation are encouraged.

The advantages of in-field vegetated buffer strips are that they are established where actual problems with surface run-off exist and thus that arable land is not taken out of production unnecessarily. They are probably also more efficient per unit area than vegetated buffer strips which are positioned more schematically according to general rules or guidelines. The scope to achieve additional positive environmental effects and to motivate farmers is higher with locally adapted design and placement[52]. The disadvantages are that the process of developing and introducing a local mitigation plan is time-consuming and requires an intensive advisory system and possibly also a monitoring system if subsidies or sanctions are to be linked to the measures.

4.1.2. Edge-of-field vegetated buffer strips

Design and purpose

An edge-of-field vegetated buffer strip is a permanent vegetated strip along the lower edge of a field and its task is to stop surface run-off flows before they leave the field. For example, it can lie along the boundary to another field, a road, a footpath or a water course. Edge-of-field vegetated buffer strips that border surface water are referred to in this report as 'riparian vegetated buffer strips' and are presented in more detail in section 4.1.3. Edge-of-field vegetated buffer strips are often covered with grass, but bushes and trees can also be planted.

Effect

Edge-of-field vegetated buffer strips are the most thoroughly investigated mitigation measure within scientific studies and consequently have the most reliably documented effects. Despite this, it is difficult to draw general conclusions on their effectiveness and design. This is partly because of the importance of local conditions for surface run-off, but also because study design and content differ considerably between published scientific studies which limit the possibilities to compare and draw general conclusions. The results of 21 scientific studies on edge-of-field vegetated buffer strips were reviewed in the course of preparing this report and the reported effectiveness for different substances is shown in Table 1. It should be pointed

Table 1. Effectiveness of vegetated buffer strips for different pesticides according to results from a total of 21 scientific studies. The results also include riparian vegetated buffer strips. The mobility classes are based on binding ability to organic material in the soil (K_{oc} values) according to the pesticide properties database (PPDB)[57]

Mobility class	Substance	Concentration reduction (%) **Mean** (min-max)	Quantity reduction (%) **Mean** (min-max)	No. of trials	References
Highly soluble compounds	DEA[1]	-	**87** (75-100)	6	18
	ETU[1]	**71** (68-74)	-	2	40
	Metribuzin	**69** (48-91)	**66** (41-91)	4	40, 58, 59
	Mean	*70*	*81*		
Moderately soluble compounds	2,4-D	-	**69**	1	60
	Atrazine	**69** (40-97)	**56** (9-100)	19	17, 18, 34, 49, 61-6316, 64, 65
	Cyanazine	-	**22** (7-38)	5	16, 61, 65
	DIPA[1]	-	**84** (45-100)	6	18
	Isoproturon	**56** (51-61)	**70** (2-100)	8	18, 66, 67
	Carbofuran	**84** (74-94)	-	2	40
	Metalaxyl	**51** (33-69)	-	2	40
	Terbutylazine	-	**38** (0-94)	6	66
	Mean	*65*	*56*		
Slightly soluble compounds	Diflufenican	**74** (73-75)	**99** (97-100)	5	18
	Lindane	-	**94** (72-100)	6	18
	Linuron	**83** (66-99)	-	2	40
	Propiconazole	-	**74** (63-85)	2	47, 68
	Mean	*78*	*92*		
Insoluble compounds	AMPA[1]	-	**67**	1	47
	Endosulfan-α	**99** (98-100)	-	2	40
	Endosulfan-β	**99** (97-100)	-	2	40
	Fenpropimorph	-	**47** (34-71)	3	47, 66, 68
	Glyphosate	-	**44** (39-48)	2	47, 68
	Chlorpyrifos	**83**	**62**	1	69
	Permethrin	-	**47**	1	63
	Mean	*96*	*50*		

[1] Degradation products (DEA=deetylatrazine, ETU=ethylenethiourea, DIPA=desisopropyl atrazine, AMPA=amino-methyl phosphoric acid)

out that most of these studies have been carried out in experimental conditions (which can be more or less realistic depending on the design of the study and the adaptation to local conditions); that the design of the vegetated buffer strips varies (e.g. width, vegetation); and that land slope and soil texture conditions vary, which can explain part of the variation in reported effectiveness. In addition, the effectiveness is affected by the moisture status of the vegetated buffer strip at the start of the study. Water-saturated vegetated buffer strips have considerably lower effectiveness than unsaturated[21, 41, 49, 53], which means that the effectiveness measured in trials with an unsaturated vegetated buffer strip may overestimate the effect of the vegetated buffer strip in wet conditions. An additional complication is that the method used for the actual effectiveness calculation differs between different studies and the difference in concentration between inflow and outflow from the vegetated buffer strip is commonly used for this purpose. Therefore it is difficult to determine how much of the reduction is due to the vegetated buffer strip being untilled and vegetated with a permanent crop and how much is due to the barrier effect created as a result of the zone not being sprayed[54]. In a comparison between grass and crop, the grass was found to reduce the amount of water to a greater extent[55], but we found no studies where the reduction in pesticide transport through surface run-off was compared between vegetated buffer strips and buffer zones (i.e. unsprayed protection strips) of equivalent width. However, for sediment transport it is probable that the effect of vegetated buffer strips is mainly dependent on the transition from crop to grass, since the greatest sedimentation occurs at the edge of the vegetated buffer strip (next the crop)[56]. Another aspect is the redistribution of pesticide transport from surface run-off to soil flows, which is often not taken into consideration in calculations of effectiveness and which means that the effect on total transport is overestimated[49].

4.1.3. Riparian vegetated buffer strips

Design and purpose

Riparian vegetated buffer strips are edge-of-field vegetated buffer strips that are directly adjacent to a water area with the aim of preventing surface run-off from reaching surface water (*Figure 9*). The definition of surface water in this context is a body of water (water course, ditch, lake, pond etc.) that is usually water-holding/water carrying. In principle, riparian vegetated buffer strips are designed and act in the same way as other edge-of-field zones, but may need to be wider to achieve the same effect, since the flows can be expected to be larger and the soil is more frequently water-saturated.

Figure 9. Riparian vegetated buffer strips. Photo: Kristin Boye.

4.1.4. Effect

Riparian vegetated buffer strips represent the most common type of vegetated buffer strip in Sweden today. According to estimates from the national inventory of the landscape (NILS), the combined length of riparian vegetated buffer strips in Sweden in 2003 was approx. 6000 km[70]. This is also the type of vegetated buffer strip referred to when a pesticide product is approved for use in Sweden on condition that a permanent vegetated buffer strip is established according to FOCUS recommendations as a risk management measure[9]. Riparian vegetated buffer strips are not as frequently examined in scientific studies, but the assessment is that they are less effective than other edge-of-field vegetated buffer strips, since 1) they are more frequently water-saturated, 2) they more frequently lie far from the sites at which surface run-off is generated and therefore the risk of concentrated flows and shortcuts is greater, and 3) water that infiltrates in the vegetated buffer strip still reaches the surface water quickly through soil flow[39]. However, it is unclear how great the difference in effectiveness is between riparian vegetated buffer strips and other edge-of-field vegetated buffer strips, since the existing scientific studies have had different designs and very few have studied actual riparian vegetated buffer strips positioned alongside water bodies. The FOCUS group reached the conclusion that the scientific data which formed the basis for their recommended risk management factors were also representative of edge-of-field vegetated buffer strips along water courses, but pointed out that the scientific data are not necessarily comparable to actual field conditions[9].

However, it should also be pointed out that the effect on the concentrations of pesticides in surface water is considered to be greatest in small water courses and ditches early in the water system[37], since the contribution of surface run-off to the total amount of water in water courses is otherwise small (the majority of the water comes from other sources). The general assessment is that despite all this, riparian vegetated buffer strips are a valuable mitigation measure, since they constitute a final filter between field and surface water. An additional advantage with riparian vegetated buffer strips is that they provide protection against spray drift[21], especially if they are vegetated with trees or bushes. However, there is a risk of pesticides trapped in the foliage of trees or bushes later being washed directly down into surface water, which can lead to the concentrations of pesticides in surface water being higher in areas with tree-clad vegetated buffer strips[71].

4.2 Wetlands

In the past few decades, wetlands have been restored, recreated or established with the aim of decreasing the loads on water recipients from agricultural land and stormwater, while at the same time increasing the biological diversity. The focus has mainly been on decreasing the nutrient loads, but wetlands have also been proven to be effective filters for pesticides[21, 25, 52, 72-74]. This is particularly the case for particle-bound compounds, where an effectiveness of close to 100% can be expected[52, 75]. For compounds that are transported in the water phase, reductions of between 77% and 99% have been reported[75], but these compounds are not as well researched as particle-bound compounds[39] and the data are therefore more uncertain.

The advantage with wetlands is that they can be established in conjunction with the recipient as a final filter[73] and they can also be used for tile drain and ditch water. In certain areas existing wetlands or water bodies can be used, which means that the costs are considerably lower and the loss of area smaller for the farmer. A method that has been used in Denmark is to divert drainage water to drained meadow that has been converted into wetland in order to promote denitrification and it is likely that pesticide concentrations will also be reduced by this treatment, although no empirical data are yet available to confirm this[9]. Newly constructed wetlands are otherwise a land-demanding measure, since it is critical that they are dimensioned according to flow and concentrations of pollutants so that the retention times are sufficiently long to allow degradation and immobilisation to occur. Vegetated wetlands are more effective than unvegetated[73], but it is important to bear in mind that herbicides can damage wetland vegetation if the concentrations are high[74]. The design and dimensions of wetlands depend on the type of pollutants that should mainly be removed from the water (for example, hydrophilic compounds require greater wetland length than hydrophobic[72]); the additional environmental benefits that can be obtained; and the magnitude of the environmental benefits in relation to the costs in the form of loss of land area, establishment costs and maintenance[74].

4.3 Ditch design

Sweden has long continuous stretches of open ditches along roads, railways, forests and agricultural land. According to estimates based on aerial photos and field inventories, the combined length of ditches alongside arable land is 71,080 km[76]. These ditches drain the field and act as the first recipient for drainage pipes and surface run-off. They thereby constitute an important transport link in the path of water from field to stream and lake[26, 77]. Studies on nutrient leaching have shown that the design of the ditches can have a great effect on the transport of pollutants[26]. Plants often have a positive effect on the retention and degradation of pesticides[33]. Having vegetation on ditch banks is also important for decreasing the risk of erosion, through the plant roots stabilising the banks[78]. Deep-rooting trees and bushes are particularly favourable from a stabilisation perspective, but could cause damage to tile drains if the soil is drained. In the USA two-step ditches are used, where a vegetated step slows down surface water flows before they reach the actual water course (*Figure 10*)[26, 79]. The step can also act as a flood shelf in order to decrease the damage to the surrounding field during high flow events. In Sweden, sedimentation ponds are used to decrease phosphorus loads. These sedimentation ponds consist of a deeper section for sedimentation, followed by one or more shallower vegetated section/s, and are installed in existing ditches or water courses to slow the flow and allow particles to sediment[26]. These ponds should presumably also have an effect on particle-bound pesticides. Another way to decrease the risk of pollutants that reach the ditch being transported onward to surface water recipients is to allow the water trench in the ditch to adopt a meandering pattern (*Figure 11*), so that the flow velocity decreases and the retention time, sedimentation time and contact with the vegetation increase[80].

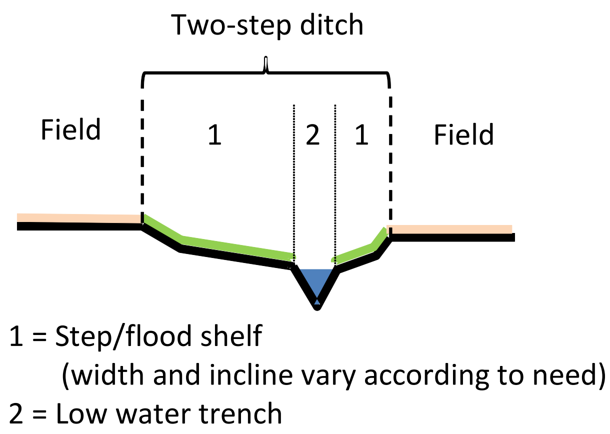

Figure 10. Principle of the two-step ditch. The step/shelf that surrounds the actual ditch trench can be restricted to one side or designed in a different way depending on local conditions.

Figure 11. Meandering water trench in a ditch with grass-covered banks. Photo: Kristin Boye.

Two-step ditches, sedimentation ponds and meanders mean that some of the surrounding arable land is taken out of production, although the areas involved are probably smaller than with other mitigation measures, such as vegetated buffer strips and wetlands. One way to decrease the area that needs to be taken out of production is to install mechanical flow barriers in the ditch to slow down the flow and increase the possibilities for retention and degradation[29, 30]. This type of measure probably requires more maintenance, since the sediment upstream of the barrier has to be removed at intervals in order to retain the effect. In the nutrient context, the possibility of installing filters of various designs and materials has been investigated and has primarily produced positive results in covered ditches[26]. If the filter consists of material that also adsorbs pesticides, this type of mitigation measure should also act to reduce the transport of pesticides.

Another important aspect regarding ditches is the effect of ditch clearing, which brings about an increase in the flow rate, decreases the vegetation cover and thereby increases the transport of sediment[78], which also gives a greater risk of leaching of phosphorus and pesticides. It is therefore important that the scope and method of ditch clearing chosen have as little effect as possible on the retention capacity of the ditch, and that the timing is restricted to when the risk of pollutant transport is as small as possible[26].

4.4 Other measures

There are a range of other types of mitigation measures that can be used to counteract surface run-off of pesticides. These can essentially be divided into two groups with different primary objectives:

- To decrease the risk of surface run-off arising.
- To decrease the risk of pesticide transport if surface run-off does arise.

4.4.1. Decreasing the risk of surface run-off

Surface run-off occurs where the infiltration capacity is limited in relation to water supply (rainfall, irrigation, etc.) or where the soil is water-saturated. Therefore, in order to decrease the risk of surface run-off, the infiltration capacity must be increased, if irrigation is applied it must be tailored to the infiltration ability or the soil must be drained if water often remains lying on the surface. The latter is often resolved by installing tile drains[39], but it is important to bear in mind that drain-flows can also transport pesticides, so the problem of pesticide loads to surface water does not necessarily decrease even if the surface run-off problem is resolved in this way[81]. Increased infiltration can also lead to pesticide transport occurring by another route, but since the flows in that case are often slower and the contact with the soil greater, there are greater opportunities for mitigating processes such as adsorption and degradation to take place. The amounts of pesticides that reach the recipient are therefore lower than they would have been had transport taken place through surface run-off[49]. Infiltration capacity can be increased by:

- Mechanical measures, *e.g. crust breaking, deep loosening to break up the plough pan, harrowing in wheel tracks, reduced tillage, tillage parallel to contour lines, avoiding compaction by not trafficking wet soil, and alternating the location of tramlines between crops.*
- Structure forming measures, *e.g. addition of organic material, no-tillage, structure liming, inclusion of deep-rooting crops.*
- Crop measures, *e.g. increased vegetation cover through an insown catch crop or other crop between crop rows (e.g. in orchards).*

Reduced tillage has been shown to be effective in decreasing the quantities of surface run-off[53, 82, 83] and often also the concentrations, although the reduced water volume as a result of increased infiltration can lead to higher concentrations if surface run-off does arise[84]. The risk of weed and insect infestation can also increase, which can lead to an increased need for chemical control measures. However, the scientific data are contradictory and some have found that the need for pesticides can remain unchanged or even decrease[85, 86]. Pesticide leaching through the soil profile can increase with reduced tillage as a result of improvements in the soil structure and increased macropore flow[84, 87, 88], but the reverse has also been demonstrated[84, 87]. The magnitude of the resulting effect on the total transport of pesticides is therefore unclear and depends to a great extent on the local situation.

Planting a catch crop between the rows of another crop can reduce pesticide transport to groundwater[89], but there are currently no scientific studies in which the effect on surface run-off has been documented. Crust formation has been shown to increase surface run-off losses of pesticides considerably[19] and structure liming can reduce phosphorus losses through surface run-off[90]. We were unable to find any scientific data on the other measures listed.

4.4.2. Decreasing the risk of pesticide transport in surface run-off

An important part of the work to decrease transport of pesticides is to decrease their use, an aspect that is also noted in the EU Directive on the sustainable use of pesticides

(2009/128/EG)[1]. In order to achieve this, there is a need for long-term planning of crop production whereby different methods are combined so as to decrease the need for chemical pesticides. This is usually referred to as Integrated Pest Management and involves adaptation of the crop rotation, tillage methods and choice of crop, together with monitoring of the pest situation so that control measures can be introduced as early as possible and other control methods (biological/mechanical control) can be applied. Chemical pest control must be regarded as a last resort and only used when absolutely necessary.

The risk of pesticides being transported with surface run-off and other flows is always greatest just after spraying[16-18]. Therefore the risks can be reduced considerably by avoiding spraying if rain is expected in the coming days, if the soil is water-saturated and if there is flow in tile drains. Choice of product can also influence the risk of transport via surface run-off, depending on the dose applied, the timing and whether the properties of the product render it more susceptible to surface run-off losses. However, it is important to bear in mind that surface run-off often transports both water-soluble and sediment-bound substances, but the relative distribution can vary depending on the magnitude and velocity of the surface run-off flows and the properties of the soil. For example, strong flows and easily erodible soils increase the risk of sediment transport.

An additional possibility to decrease the risk of transport of pesticides through surface run-off can be to increase the soil organic matter content, which increases the adsorption ability, stimulates degradation and decreases the risk of erosion. This can be achieved for example through mixing organic material into the soil, using a catch crop, reduced or no tillage.

4.5 Combined environmental benefits

Many of the mitigation measures that are proposed regarding surface run-off of pesticides are also used as mitigation measures regarding transport of nutrients and other pollutants. They also automatically mean that biological diversity and the conditions for various ecosystem services are increased to some extent. However, in most cases it is impossible to achieve maximum effect for each individual environmental aspect and it is therefore important to consider what is most important to prioritise in different contexts and then optimise the choice of mitigation measures and their design so that the combined environmental benefit is as great as possible. It is also important to remember that for nutrients, it is often the total load that is critical, while for pesticides the peak concentrations are often more critical. This can mean that a mitigation measure that effectively decreases the total transport of pollutants during the year, but is unable to withstand a heavy temporary load, will not have any discernible effect in the form of decreased toxicity and mortality in aquatic organisms.

Most scientific studies on surface run-off and mitigation measures tend to concentrate on one or a few different types of pollutants and one type of mitigation measure. However, there is now increasing interest in studying multifunctionality[91] and optimisation potential as regards the cost versus the environmental benefits[92].

4.5.1. Phosphorus

Phosphorus and pesticides display many similarities as regards transport mechanisms and flow pathways. Pesticides that are water-soluble and readily soluble are transported in the water phase in the same way as dissolved reactive phosphorus, while particle-bound substances (including phosphorus) are transported with suspended material and are more susceptible to erosion. This means that the same types of mitigation measures can be used for phosphorus and pesticides, with the main difference being that phosphorus requires the measure to operate during snowmelt, when high phosphorus transport occurs via surface run-off, while the majority of pesticide transport probably occurs during the growing season. In vegetated buffer strips phosphorus is also generally more sensitive to saturation and re-leaching, since it is not broken down but simply changes chemical form and phase[26]. Therefore the long-term effectiveness of vegetated buffer strips in terms of phosphorus retention has been questioned[26], even though the effectiveness appears to be able to persist[93] or even increase[50], provided that the vegetated buffer strip is managed and that infiltration continues to be high or increases with progressive root growth[50]. Vegetated buffer strips with tree vegetation are reported to give higher retention of phosphorus and nitrogen than vegetated buffer strips covered with grass[94].

Owing to the fact that phosphorus is a nutrient that circulates in nature, the mitigation measures mentioned above are often not as effective as for pesticides and the effectiveness also varies to a considerably greater extent between different scientific studies. For vegetated buffer strips, phosphorus reduction effects in surface run-off of up to 90% have been reported[18], but the values vary widely and sometimes the effect may even be negative, i.e. phosphorus is mobilised in the vegetated buffer strip and leaching increases[95]. A reasonable expectation is therefore an approx. 50% reduction[26]. Swedish trials have found phosphorus retention of between 0 and 95% in vegetated buffer strips[96, 97]. For wetlands in Sweden, phosphorus removal effects of between 1 and 90% have been reported[98]. This large variation in effectiveness has been attributed to differences in local conditions[26].

4.5.2. Other pollutants

Mitigation measures directed at surface run-off of pesticides should theoretically also have an effect on other pollutants that have similar characteristics and are therefore transported and immobilised or broken down through the same mechanisms. However, there is very limited research concerning the effect of mitigation measures on other types of pollutants, with the exception of nitrogen. In order to decrease nitrogen loads it is important to promote the denitrification process, which means that organic material is required and that alternating anaerobic and aerobic conditions must be created. For this reason, water-saturated and/or tree-clad vegetated buffer strips[94], in-ditch measures and wetlands are often more effective than other mitigation measures.

Research results show that vegetated buffer strips are often less effective in controlling nitrogen (25-60% for total nitrogen content[47, 99]) than they are in controlling phosphorus and pesticides and the effect is sometimes negative[54]. However, the effect can be close to 100%

for nitrate-nitrogen under suitable conditions[18]. Vegetated buffer strips also effectively reduce the nitrate concentrations in soil flows that pass through the rootzone[54, 100].

4.5.3. Biological diversity

The opportunities for promoting biological diversity, while also obtaining other environmental benefits in the form of decreased pollutant loads in surface water bodies, should be great in vegetated buffer strips. Vegetated buffer strips that are vegetated with herbaceous plants can provide a habitat or create important interconnections in the landscape that increase the diversity of pollinating insects[101, 102], while bush or tree vegetation can attract small mammals. Bushes and trees also provide important shade and add organic material to water courses and ditches, which leads to increased biotope richness for aquatic organisms[91]. Wetlands represent a threatened habitat and the restoration, recreation or creation of wetlands can therefore benefit animals, plants and other organisms that are dependent on this type of biotope for their survival.

It is important to mention that for biological diversity to be favoured in the best way, a greater area is often required than for decreasing pollutant loads. If vegetated buffer strips are to have a beneficial effect for pollinating insects, there is often a need to have similar biotopes in the vicinity (e.g. meadow) and the effect is greater in forested landscape than in agricultural landscape[101-103]. In order to benefit small mammals and other animals, the strip must be sufficiently wide and there must be continuity in the landscape (‘green corridors’).

The weed pressure can increase in the field if the vegetated buffer strip is favourable for weed species[37]. The same applies for insect attack[37]. It is unlikely that the biological diversity of plants will be promoted to a particularly great extent[104], since vegetated buffer strips tend to be nutrient-rich[35] and therefore many rare species cannot compete against ruderal species (i.e. plants that thrive in nitrogen-rich soil). An additional important aspect is that herbicides can be damaging for the vegetation in vegetated buffer strips and wetlands if the concentrations become sufficiently high.

5. Surface run-off of pesticides in Sweden

Surface run-off is an issue that has not been examined particularly thoroughly in Sweden, partly because of the large proportion of drained agricultural land, where the problem has been assumed to be negligible. Therefore there is great uncertainty regarding how extensive the problem actually is in time and space. Norwegian studies show that surface run-off of pesticides occurs in that country, especially from erosion-prone soils[88]. Swedish researchers working on phosphorus leaching report that surface run-off can be of local significance, primarily during snowmelt, but it is unclear how much transport occurs via this route[105, 106]. Computer simulation data used for calculating phosphorus leaching from arable land in Sweden show that surface run-off represents 2-37% of total run-off, depending on soil type and region, but owing to the limited data support for calibration and validation of the model, these figures are uncertain[107]. The only empirical data from Sweden found in the work of compiling the present report originate from an observation field (14AC) in Västerbotten that forms part of the national programme for environmental monitoring of nutrients[108]. The soil at the site is silt loam, with a relatively high humus content (2.2%) and a slope of 1%. The field is tile-drained and surface run-off flow is measured in a ditch (*Figure 12*), which means that it most likely also includes lateral superficial flows in the soil. Therefore the flow quantities recorded (*Figure 13*) are probably higher than the actual surface run-off.

For pesticides there are currently no empirical data available. A scrutiny of environmental monitoring data from a type area in Östergötland was unable to demonstrate that surface run-off had contributed to the guideline values for pesticides in surface water being exceeded, but was also unable to completely exclude the possibility of surface run-off transport[109]. The lack of data makes it difficult to assess the actual magnitude of pesticide transport from field to surface water through surface run-off. In contrast to phosphorus, pesticide transport through surface run-off in conjunction with snowmelt is often assumed to be negligible, since spraying of pesticides takes place during the growing season and most compounds currently in use are broken down relatively quickly in the soil. However, a Finnish study which compared three herbicides (glyphosate, gluphosinate-ammonium and ethofumesate) applied to bare soil in July showed that transport in conjunction with snowmelt in the following spring represented the greatest proportion of total transport, although the concentrations were very low[110].

Figure 12. Left: Observation field for environmental monitoring of nutrients in Västerbotten. Right: Surface run-off measured in the ditch. Photo: Maria Blomberg.

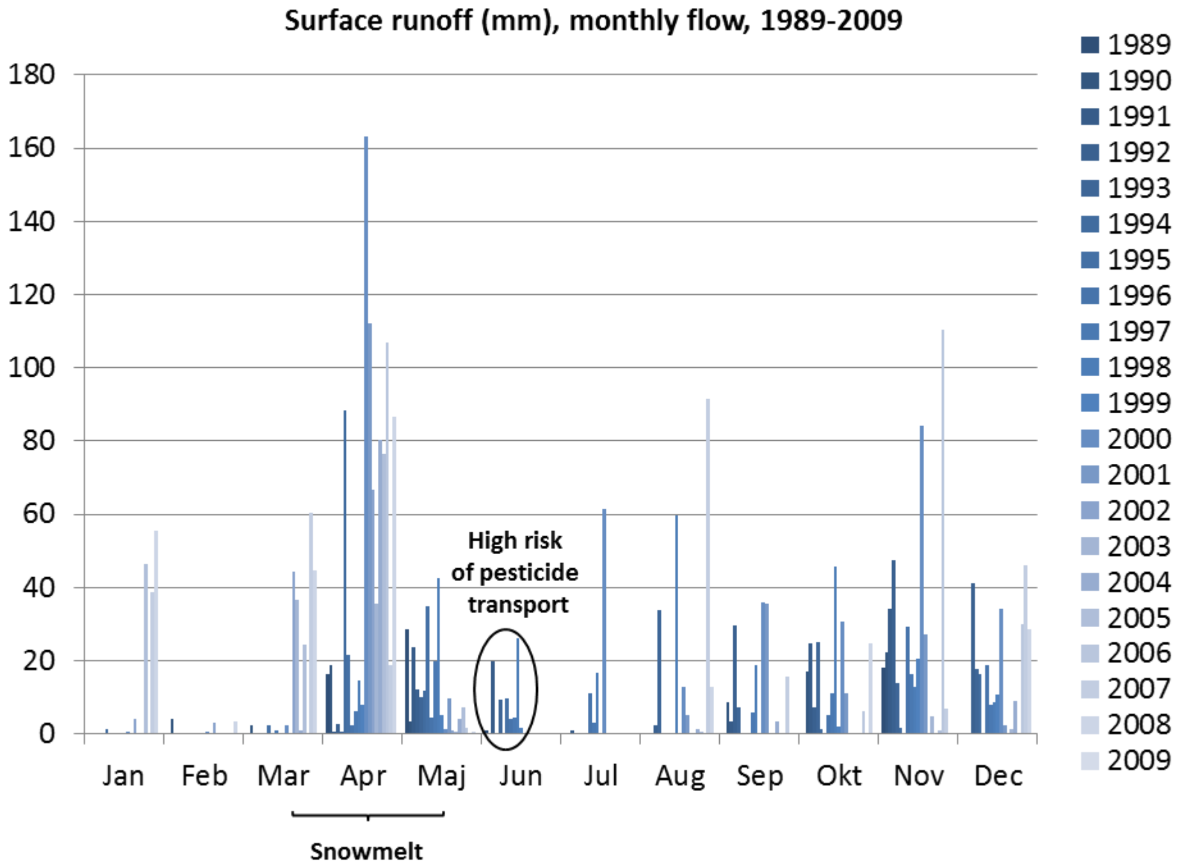

Figure 13. Measured monthly flows in the form of surface run-off from observation field 14AC for environmental monitoring of nutrients. Snowmelt occurs in the period March-May (depending on annual variations) and the greatest risk of transport of pesticides probably arises in the beginning of the growing season (June) when herbicide use is greatest. According to the measurements, surface run-off in June occurred in 7 years out of 21, i.e. on average every three years, but two years (1991 and 1998) were responsible for a total of 78% of the total surface run-off during the month of June.

Surface run-off transport of pesticides during winter has also been reported in Norway[88]. In addition, surface run-off does not solely occur during snowmelt in Sweden. Individual observations (*Figure 2*) and data from the field in Västerbotten (*Figure 13*) show that surface run-off also occurs during the summer and particularly during the autumn, despite the fact that the field is drained. Surface run-off during the summer months varies widely from one year to the next, since it is an episode-based event, and the data show that on average surface run-off occurs during the most intensive spraying month (June) in one year in three and that there are significant flows in one year in ten (*Figure 13*). However, it is difficult to draw conclusions on the extent of the problem based on these individual observations and measurements. Expert opinion is that surface run-off during the growing season takes place from a minor proportion of agricultural land that is particularly susceptible due to soil texture, slope or degraded soil structure, and during short periods, for example thunderstorms or heavy rain after a period of drought. There is great uncertainty as regards flow quantities, concentrations of different pollutants and the proportion of the surface run-off flows that do occur actually reaching surface water courses (i.e. connectivity of flow pathways). It is important to point out that even if the total transport of pesticides is low, in unfavourable conditions the concentrations can be so high that they have a damaging effect on aquatic organisms[55].

6. Models

6.1 Risk assessment

An inventory of the true extent of the surface run-off problem in Sweden would require major inputs in the form of time and resources. Instead, different models can be used to assess the magnitude of risk of various substances being transported with surface run-off flows, areas that are particularly vulnerable, etc. At present, the R1 scenario in the PRZM-in-FOCUS model[7] is used by KemI for risk assessment of surface run-off losses when plant protection products are being approved for use in Sweden. Phosphorus losses via surface run-off are calculated with the help of the ICECREAM model, where the relative distribution of infiltration and surface run-off is dealt with in a similar way as in PRZM. The difference is that ICECREAM is a refined version of the CREAMS model from the USA[111], adapted to the Nordic climate[112, 113] and Swedish soil conditions[114], while PRZM has not been adjusted to Swedish conditions. At present, CKB is working to develop a MACRO model that will allow risk assessments of surface run-off and erosion losses from individual fields (MACRO-DB) and identification of specific risks of surface run-off arising within a catchment area (MACRO-SE). The model will be tailored to Swedish conditions and validated against Scandinavian data. Other countries are also developing models focusing on identification of risk areas on the basis of geographical data, which are relatively easy to obtain[115-119].

An essential precondition for the reliability of model results is that they must be calibrated against actual data that are representative of the area under study. Since there are currently no field data on surface run-off of pesticides in Sweden, it has not been possible to validate the models used for calculating surface run-off losses against domestic data. However, the soil texture and weather data in the FOCUS R1 scenario have been evaluated based on Swedish conditions. Statistical analysis of the representativity of soil texture has shown that the soil texture in the R1 scenario is more prone to surface run-off than any of the Swedish soil textures sampled within the soil and crop inventory of Swedish agricultural soil[120] (

*Figure **14***). That analysis was based on the assumption that high silt content and low organic matter content are the main soil characteristics determining whether surface run-off will be created, which is reasonable since silty soils are often prone to erosion, have a weak structure, are very susceptible to puddling and form a crust on drying, while organic material promotes aggregate formation and infiltration. In order to assess how an extreme (for Swedish conditions) soil texture affects the risk assessment of surface run-off of pesticides, the R1 scenario in the PRZM model was run with a soil texture that represented a feasible worst case scenario (90th percentile) with respect to silt and organic matter content and using meteorological data from west Götaland. The results showed that surface run-off flows during the summer months were overestimated when the R1 scenario was run with the original data, compared with what can be considered a reasonable level of probability (90th percentile) for Swedish conditions (

*Figure **15***). For the risk of erosion, the differences were even greater (

Figure ***15***). In comparison with data from the observation field in Västerbotten, the erosion losses according to simulations with the original R1 scenario were 10-fold higher.

6.2 Risk management

In addition to being used in risk identification and risk assessment, models can also be used to test different risk management measures. For vegetated buffer strips there are a number of different alternatives. The simplest and most common approach is for a reduction factor to be applied in simulation of surface run-off transport. This reduction factor is based on the effect of vegetated buffer strips according to scientific studies and can be adjusted if the effect is to vary with different strip widths, substance mobility classes or other factors considered capable of affecting the effectiveness of the vegetated buffer strip. For small recipients, it is important that the reduction in the amount of water transported as surface run-off is also taken into account, so that the final concentrations in the recipient are adjusted to the volume of water. This is done e.g. in the model used in Germany for risk management calculations, EXPOSIT[121]. The PRZM-in-FOCUS model can also be complemented with a reduction factor for mitigation measures. When KemI grants approval for a product on condition of a permanent vegetated buffer strip, this is based on simulations in SWAN with a reduction effect of 60% for water-soluble and 85% for particle-bound substances for a 10-12 m wide vegetated buffer strip. These effects represent the 90th percentile of the mean effect according to reports from scientific studies in Europe (compiled by the FOCUS group) and are considered by FOCUS to be reasonably conservative[9].

This is despite the fact that the supporting data are limited and differ considerably between scientific studies and that the study conditions are not directly comparable with actual conditions in the field[9]. The FOCUS report also points out that the literature reviewed only includes studies where the flow reaches the vegetated buffer strip as uniform surface flow (sheet flow), where the vegetated buffer strip is unsaturated and where infiltration capacity is not reduced by surface crusting[9]. Evaluations of the validity of the FOCUS simulations for

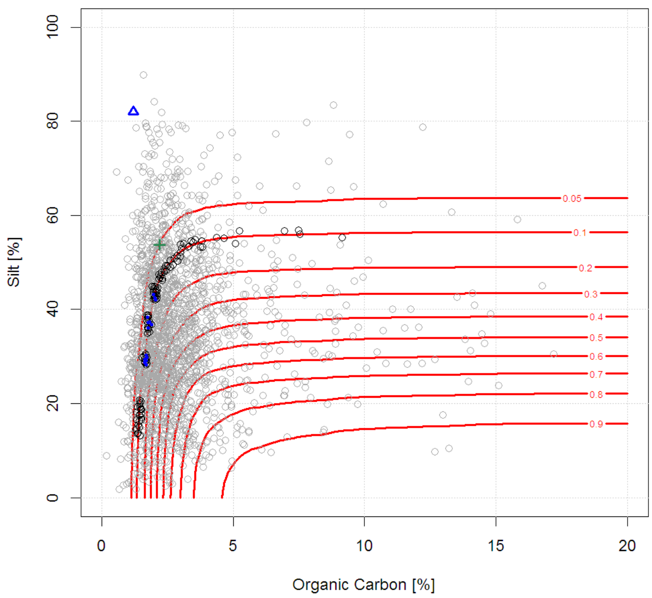

Figure 14. Concentrations of organic carbon (x-axis) and silt (y-axis) in Swedish soils according to data from environmental monitoring of Swedish arable soils (grey circles). The curves show the proportion of soils that fall above and to the left of the line. The observation field (14AC) in Västerbotten (green + sign) is on the curve representing the 95th percentile, while the soil in the R1 scenario (blue triangle) falls outside the concentrations found in Sweden. Soils with concentrations corresponding to the 90th percentile are marked with black circles and of these, the most reasonable 'worst case' soils are marked in blue.

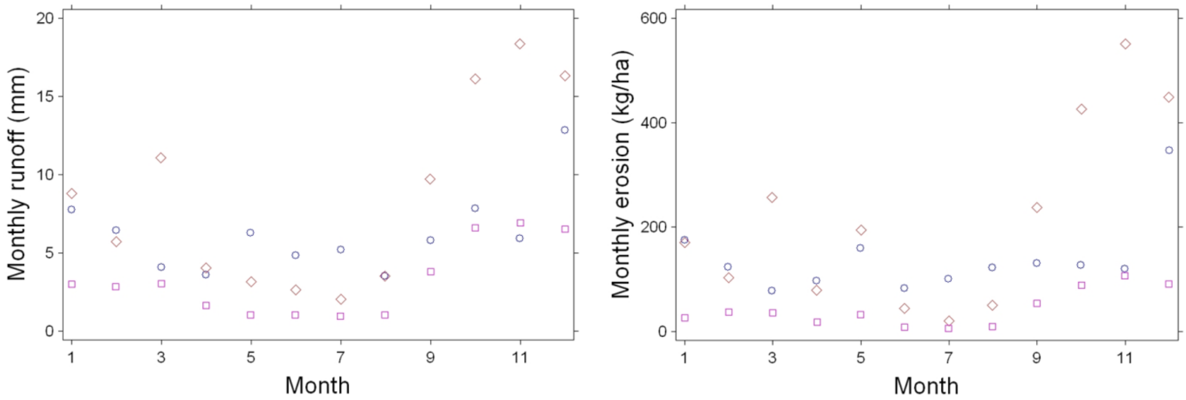

Figure 15. Simulated monthly surface run-off (left) and monthly erosion (right) according to the PRZM model with scenario R1 in the original according to FOCUS[7] (blue circles), with Swedish meteorological data (brown diamonds) and with Swedish soil and meteorological data (pink squares).

actual vegetated buffer strips have shown that the effectiveness is lower than predicted owing to non-optimal conditions in the field, for example in the form of incomplete vegetation cover and/or footpaths causing concentrated flows[122].

Use of simple risk management factors in model calculations can in many cases be perfectly adequate, but the effectiveness of vegetated buffer strips can vary depending on soil conditions, substance characteristics, the extent and velocity of surface run-off flows and whether concentrated flows arise[44]. In order to obtain a more dynamic picture of the effectiveness of vegetated buffer strips, the processes within the actual strip can be modelled. Researchers in the USA have developed a model, VFSMOD-W[123-125], that calculates outflow, infiltration, sediment immobilisation and pesticide reduction in vegetated buffer strips. The reduction in pesticides is the result of infiltration, sediment reduction, the clay content in inflow and a pesticide distribution factor between the water and sediment phases. The model can be coupled to models that calculate surface run-off flows. Work to develop EU scenarios for vegetated buffer strip modelling with VFSMOD-W coupled to PRZM-in-FOCUS scenarios for surface run-off (R1-R4) has recently been completed[126]. The intention is for these to be suitable for use in making risk management calculations in conjunction with product registration within the EU. However, as with the PRZM modelling work, it is important that the data used in modelling are representative of the area in which the product will be used. For VFSMOD-W it has been concluded, in validation against field data, that the saturated hydraulic conductivity in the vegetated buffer strip is the most important parameter for the estimated effectiveness of the vegetated buffer strip[44, 126, 127]. It is therefore particularly important that the value used for this parameter is representative of the soils to be modelled. Saturated hydraulic conductivity is linked to soil structure and is reduced by soil compaction, for example in wheel tracks[128]. Therefore the local variation can be great, which should be borne in mind when evaluating the results of modelling work.

Models are also being developed to calculate the total effect of combined mitigation measures and efforts within a catchment area[129] or to help optimise effectiveness in relation to cost (cost-benefit) in the design and selection of mitigation measures[92, 130].

7. International research

The issue of surface run-off has been studied to varying degrees in different countries. Most scientific studies, models and mitigation measures originate from the USA, where the problem has long been recognised, and guidelines for the construction of conservation buffer zones to reduce pesticide losses were issued by the United States Department of Agriculture back in 2000[37]. Within Europe, France in particular has contributed through research and development of the CORPEN method[29, 30, 38] for use in inventories of soil requirements and application of different mitigation measures, through a collaboration between the Cemagref research institute and the Arvalis advisory body. In the United Kingdom too, a substantial amount of research has been carried out on mitigation measures to control non-point sources, but primarily of nutrients. In an on-going successful partnership between Natural England and the British Environmental Protection Agency, particularly susceptible catchment areas are being selected for targeted mitigation projects at farm level (often a group of farms within the same area), which are then followed up with monitoring of surface water status[32]. With the new EU Directive on the sustainable use of pesticides[1], the issue of safe-guard zones and vegetated buffer strips has become relevant in all EU countries. Since in many countries, including Sweden, implementation of the directive into national legislation and the formulation of national action plans has been severely delayed, it is still unclear how the issue will be handled.

Table ***2*** summarises the available information on how vegetated buffer strips are currently being handled within the EU.

There is also a lack of clarity concerning how the funding of different mitigation measures should be handled. Sweden has opted not to provide subsidies for mitigation measures that are required by law, but in Denmark compensation is promised for the establishment of those vegetated buffer strips (10 m) which according to the new law[131] must be in place along all water courses from 1 September 2012. In Italy, the requirement is for vegetated buffer strips (5 m) to be established along water courses in order to qualify for support for rural development, i.e. the compulsory vegetated buffer strips are included as a form of cross-compliance for the granting of another type of subsidy[126]. In addition, support is provided for the implementation of other mitigation measures (e.g. hedges, rows of trees, extended riparian vegetated buffer strips with woody vegetation) in certain regions of Italy[126]. In the UK, mitigation measures to control surface run-off and erosion where problems exist is a precondition for eligibility for support within the Single Farm Payment Scheme, in which the basic requirement is that farmers must demonstrate that the land is being kept in good farming and ecological condition[132]. A similar system is proposed for the new common agricultural programme (CAP) within the EU, whereby green payments will be made to farmers who meet certain environmental criteria, including setting aside 7% of their land for ecological benefits[133]. Vegetated buffer strips and wetlands may be eligible for inclusion in the area set aside for ecology.

Table 2. Current handling of buffer and vegetated buffer strips in national legislation and risk assessment in some EU countries

Land	Legislation: Compulsory buffer zone around water courses	Product registration: Simulation of mitigation measures accepted
Denmark+	10 m (crop-free)	No (investigation in progress)
France+	5 m (crop-free)	Yes, FOCUS-SWAN (R1-R4)
Holland+	25 cm-9 m (crop-free)	No (investigation in progress)
Italy+	5 m (spray- and plough-free, exceptions occur)	Yes, FOCUS-SWAN (R3, R4)
Poland++	20 m (permanently vegetated) 5 m along roads (permanently vegetated)	Information lacking
Germany+	1-3 m (spray-free)	Yes, Exposit ([poss. FOCUS)
Slovakia++	12 m (permanently vegetated)	Information lacking
UK+	2 m (crop-free)	No (investigation in progress)
Sweden+	6 m (crop-free, proposal)	Yes FOCUS-SWAN (R1)
Hungary++	5 m (permanently vegetated)	Information lacking
Austria+	1-3 m (permanently vegetated)	Yes, FOCUS-SWAN (R1, R3)

+ Hughes and Brown 2011[134]

++ ARVALIS 2004[135]

8. Conclusions

8.1 Evaluation of the applicability and predicted effect of mitigation measures in Sweden

In order to evaluate the relevance of international scientific data for Swedish conditions, the factors determining the effectiveness of a mitigation measure must be identified. By far the most important factor for a mitigation measure to have an effect is that transport of pesticides through surface run-off actually occurs in the first place and that the mitigation measure is targeted towards the sites and occasions where surface run-off occurs. Since there is major uncertainty regarding the overall magnitude of pesticide transport through surface run-off in Sweden, it is impossible to predict the potential effects of mitigation measures on the amounts and concentrations of substances detected in surface water. Studies from Denmark show that vegetated buffer strips decrease the concentrations of pesticides in surface water courses[136] and can improve the ecological quality of water courses and of the soil immediately adjacent to water courses[137]. A study in Germany concluded that a spray-free buffer zone along a water course was critical in decreasing pesticide transport to that water course[118]. It is likely that these results are also applicable in Swedish conditions. However, land drainage is considerably more common in Sweden than in for example France, where much of the existing European research has been carried out, and vegetated buffer strips are considered not to be effective on drained soil unless surface run-off transport is still considerable for some reason[9, 21, 100]. This can mean that the effect of vegetated buffer strips on total transport of pesticides is less in Sweden than in France. Swedish arable soils are often less strongly sloping and have a more well-developed structure and a higher infiltration capacity than the erosion-prone loess soils in eastern Europe and the strongly sloping silty soils in the

Mediterranean area that are used in the R scenarios in PRZM-in-FOCUS. It therefore appears reasonable to assume that the amounts of pesticides transported with surface run-off are lower in Sweden than in those countries where much of the research on mitigation measures has been carried out. Therefore it is also reasonable to assume that mitigation measures specifically targeted towards surface run-off have a lower effect on the total amount of substances detected in surface water in Sweden than in countries with considerable surface run-off.

However, there is no reason to suspect that the effectiveness of mitigation measures on the transport that actually occurs via surface run-off would be lower in Sweden than in other countries. Research carried out in Norway[47], Finland[50] and Denmark[136] shows that in the Nordic climate too, vegetated buffer strips have an effect on pollutant transport through surface run-off. This is reasonable, especially for pesticides, since losses of these occur primarily during the growing season, when the vegetation and soil processes in vegetated buffer strips, ditches and wetlands are fully active. If spraying is carried out early in spring or late in autumn, however, the effect of, for example, a vegetated buffer strip can be expected to be lower than that reported for warmer countries. It is also possible that the effect of vegetated buffer strips is influenced by early summer drought, which occurs in parts of Sweden, but we were unable to find any scientific studies examining the influence of dry conditions on the effect of vegetated buffer strips. However, it has been reported that soil moisture content in a vegetated buffer strip is significant for its effectiveness, but this primarily concerns water-saturated conditions being considerably worse than unsaturated[41, 53].

8.2 Recommendations

8.2.1. Research and environmental monitoring

Knowledge on surface run-off of pesticides in Sweden is currently limited. There is a lack of field data and scientifically based information on the size of the flows that occur and the extent to which pesticides are transported in the flows. Therefore, priority should be given to research that aims to chart the importance of surface run-off in pesticide transport from Swedish arable land. Such research should focus on identifying:

1. The main transport pathways for the pesticides detected in surface water. The importance of surface run-off to drainage wells and ditches should be the subject of particular attention.
2. The topographical, meteorological, agricultural and soil-specific conditions that determine the path water takes from field to surface water.

The results of this type of research should be used to develop, calibrate and validate models for simulating pollutant transport, which are essential in creating an overall estimation of the relative importance of non-point source pathways for nutrient and pesticides losses from Swedish arable land. Owing to run-off events being of an episodic nature and tending to vary greatly between years, it is essential that measurements are carried out over long periods (preferably >10 years). At present, CKB is carrying out two research projects with the aim of generating field data on flow pathways for pesticides and it is important that these projects be allowed to continue, preferably complemented with other trial sites.

One way to achieve continuous measurements on the extent of surface run-off and its importance for transport of pesticides is for environmental monitoring of pesticides to be complemented with measurements of surface run-off on one or more observation fields within the type areas. This would require additional operating funding for sampling and analysis, as well as start-up funding for installation of measuring equipment etc.

The current mapping work being carried out within CKB with MACRO-SE based on soil texture maps and the National Land Survey of Sweden's new high resolution topographical maps is scheduled for completion in winter 2012/2013. The work is generating regional or catchment area-related risk classification maps for areas susceptible to surface run-off. These maps can use used for example for targeted measures or linked to area-specific conditions of use for pesticide products.

Research into mitigation measures against surface run-off should also be promoted. The focus of such research should be on:

1) Actual effects of mitigation measures on pesticide concentrations and quantities in surface water.
2) Choice of mitigation measure and specific designs for achieving the greatest cumulative benefit possible at the least possible cost (multifunctionality with respect to e.g. pesticides, nutrients and biological diversity).

8.2.2. Risk assessment

The scenario (R1) in PRZM-in-FOCUS that is currently used by KemI to assess the risk of a substance being transported through surface run-off to surface water is not specifically designed for the Swedish climate and Swedish soils. It is likely that the model overestimates the risk of surface run-off of pesticides, and therefore an alternative should be considered. However, changing the process used for product approval is not without its complications. According to the harmonisation principles in the EU pesticide directive (EG 1107/2009)[2], product approval is only required in one country in order for use to be permitted throughout the harmonisation zone. A new scenario that gives a more realistic assessment of risk under Swedish conditions would therefore mean a specific simulation for approval in Sweden. Furthermore, there is currently a lack of the data required to carry out complete calibration and validation of the models. However, it is reasonable to assume that if Swedish input data are used in the simulations, the output data will represent Swedish conditions more accurately than when the data from the R1 scenario are used. The results presented in this report led to the generation of two suggested alternatives to the current risk assessment with the R1 scenario:

- Continued use of PRZM-in-FOCUS, but with a Swedish scenario where Swedish soil texture and climate data are used in the modelling work.
  Advantages: A rapid solution, the model is well-established in the appraisal process, representative 'worst case' (90th percentile) data for soil texture and climate can

be produced relatively easily, risk management evaluations of vegetated buffer strips can be made with VFSMOD-W if required.

Disadvantages: Parametrisation of the model must be carried out by a PRZM expert (CKB does not possess the competence to do this), data for calibration and validation of the simulation results are currently lacking.

- A change to using the MACRO model with a scenario where data are taken from Näsbygård in Skåne. The soil texture at Näsbygård corresponds to the 90th percentile for Swedish arable land.

  Advantages: The MACRO model is already used for simulating the risk of leaching to drain-flow and groundwater in the product registration process, and for permit approval in water protection areas. Data from Näsbygård are used for the groundwater simulations. CKB possesses the competence to develop, calibrate and validate the model and the scenario if the supporting data are sufficient.

  Disadvantages: The risk assessment process would be further complicated by using a different model for surface run-off simulations than in the other countries in the northern zone. VFSMOD-W cannot be linked to MACRO for modelling the effect of vegetated buffer strips. A more long-term solution.

One option is to retain the current risk assessment with R1, but introduce the possibility to proceed with one of the alternative scenarios listed above if the R1 simulations indicate a risk.

8.2.3. Risk management and mitigation measures

A critical issue for the Swedish authorities concerns how to interpret the introduction of the water protection zones required by the EU directive on the sustainable use of pesticides (2009/128/EG Ch. 4, Article 11, paragraph 2c)[1]. Should this zone consist of a spray-free zone and therefore correspond to the current pesticide buffer zone, or should it be a permanently vegetated buffer strip? The advantage with general compulsory vegetated buffer strips is that administration and inspection are easier compared with when local measures are introduced, and that risk management with a vegetated buffer strip can automatically be included in the product registration process, so that the conditions do not need to be linked to specific products. However, in Denmark difficulties have arisen as a result of inaccuracies in the map material used today to identify water courses that are covered by the statutory requirement and the administrative benefits are thus not self-evident. In addition, the cost-effectiveness is considered to be higher if vegetated buffer strips are only established in critical areas[138, 139]. It can also be more difficult to motivate farmers to establish vegetated buffer strips, despite the legal requirement, if no direct link to actual risk exists on the basis of their soil and crop production conditions. This is particularly the case if there is no economic compensation provided for loss of income and expenses for establishing and maintaining vegetated buffer strips. Based on the knowledge acquired in the work on this report, the following conclusions can be drawn:

1) Despite the very limited scientific data support, it appears that only a small proportion of agricultural land in Sweden is subject to surface run-off to any significant degree during the growing season, and therefore having general vegetated buffer strips would

mean taking large areas of agricultural land out of production without discernible effects on pesticide transport to surface water.

2) International experts are unanimous that local adaptation of mitigation measures after an inventory of need is necessary for achieving an effective reduction in transport of pesticides through surface run-off.
3) Riparian vegetated buffer strips are often less effective than other edge-of-field vegetated buffer strips.
4) Riparian vegetated buffer strips mainly have an effect on pollutant concentrations in small water courses early in the water system and these are not necessarily always marked on the map, which causes difficulties in deciding what should be included in the concept ‘water course’.
5) Ditches and drainage wells are probably important transport pathways for pesticides in Sweden and these are normally not included in the concept ‘water course’.

Against this background and on the basis of knowledge acquired during the work on this report, it does not appear to be justified to legislate for compulsory vegetated buffer strips along all water courses in Sweden.

Our assessment is that despite this, surface run-off locally can be significant for the total transport of pesticides to surface water in Sweden. Mitigation measures against surface run-off should therefore be implemented and the focus should be on local adaptation and multifunctionality, i.e. optimisation of the total environmental benefit through adaptation of the mitigation measures to local conditions. There is good potential to combine measures against nutrient and pesticides losses. Furthermore, the biological diversity can probably also benefit in many cases. Locally adapted solutions also increase the opportunities to motivate and involve farmers in the planning of mitigation measures, which is important in achieving long-term effects[52]. There are different conceivable solutions for how locally adapted measures against surface run-off should be organised:

- The existing environmental subsidy for establishment of adjusted buffer zones on agricultural land in order to prevent nutrient losses is extended and revised to include all types of vegetated buffer strips established, with the aim of decreasing surface run-off flows and erosion from arable land. The subsidy should realistically be linked to a specific risk of surface run-off, according to field observations and/or modelled risk assessment.
- An advice-centred system based on the CORPEN methodology is developed. The decision tree and the report from the TOPPS-Prowadis project can be used as starting material, but adaptation to Swedish conditions may be necessary. Training for advisors may be needed. Funding options need to be investigated.
- Legislate for compulsory measures against surface run-off in areas where there is a particular risk of surface run-off occurring. Such areas can be identified for example with the aid of MACRO-SE, based on the National Land Survey of Sweden’s high resolution topographical maps and soil texture maps. The legislation can apply generally for all agricultural land within the area, or for the use of chemical pesticides in general or only

use of products with a particular risk of surface run-off leaching. The possibilities for compensation and support need to be investigated.

- Even if mitigation measures against surface run-off are introduced on a voluntary basis, successful implementation may mean that the risk of surface run-off of pesticides is considered to be sufficiently small to render risk assessment unnecessary in the product registration process.
- The new common agriculture programme (CAP) within the EU according to the current proposal will contain the requirement that to receive support payments farmers will have to set 7% of their land aside as an 'ecological focus area'[133]. This land can be used for example to implement mitigation measures against surface run-off should the need arise. It is important that these ecological focus areas create as great an environmental benefit as possible, which can mean that regulatory and/or advisory inputs are required to optimise the choice of land use (e.g. vegetated buffer strip, wetland, tree planting, fallow) and positioning based on local conditions.

Irrespective of the type of solution chosen, a decision must be made on the magnitude of risk considered to be acceptable. Where should the limit be drawn regarding which water courses and lakes should be protected (size, type, ecological value, etc.)? How often can surface run-off transport of pesticides as a result of extreme conditions be accepted (every 5, 10, 50 or 100 years)? What is an acceptable level of reasonable risk and uncertainty in parametrisation and selection of data for modelling (is the 90th percentile sufficient if the values are very uncertain or the variation great)?

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